

Review Article

A Review on the Overview of Trichoderma - A Versatile Biocontrol Agent and Plant Growth Promotor

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Abstract

Trichoderma is an economically important microorganism that arises from farming fields to industry. Trichoderma species are beneficial microorganisms in agro-ecosystems, enhancing soil health, promoting crop growth, and encouraging the uptake and utilization of micro- and macronutrients through mutualistic endophytic associations. It regulates microbial interactions and influences the soil microbiome through direct antagonism and competition, particularly in the rhizosphere. Trichoderma species serve as biocontrol agents and enhancers of plant growth, highlighting their pivotal role in advancing sustainable agricultural practices. This study explored the ecological flexibility of Trichoderma, which thrives in soil and forms beneficial relationships with plants, leading to improved nutrient uptake, increased crop yields, and greater disease resistance. This review discusses the potential of Trichoderma in promoting plant growth through the solubilization of nutrients and the production of phytohormones, reducing the reliance on chemical fertilizers and pesticides. As eco-friendly substitutions to conventional chemical pesticides in disease management and crop development, biocontrol agents have gained prominence. Species of Trichoderma possess grown into a flexible tool for biocontrol, biofertilization, and phyto-stimulation, and they assemble a key microbial community that impacts climate-resilient agriculture. Recent studies have highlighted Trichoderma's capacity to improve soil health and establish sustainable farming methods, making it an essential element in tackling environmental sustainability and food production problems.

Keywords

Trichoderma, Biocontrol Mechanism, Phytohormones, Endophytic Association, Sustainable Farming, Disease Resistance

1. Introduction

Agriculture's impact on the environment is significant, but it can become more harmonious with nature through sustainable practices and innovation. Balancing the need for food production with environmental protection is critical for ensuring a healthy planet and future generations' food security. It depends on balancing sustainability and productivity. Combined with traditional knowledge, technological innovations can generate a more resilient and effective agricultural

system. Policymakers' support and funding for R&D are crucial for addressing issues and securing opportunities in the agricultural sector.

We can guarantee agriculture and humanity a sustainable and successful future by resolving their challenges and embracing improvements. A growing trend in sustainable agriculture is the use of biocontrol and bio-stimulate agents, particularly for fungi. Biological (BCAs), which are based on

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live microorganisms or their metabolites and naturally occurring products that regulate plant pathogen populations, are among these techniques. A significant amount of work has been done in the last few decades to investigate the viability and efficacy of nonpathogenic bacteria and fungi to promote them as BCAs [1]. Using well-known species; *Trichoderma*, *Beauveria*, and *Metarhizium*, are examples. Certain distinct qualities are necessary for an efficient and possible BCA to enable successful bio-control of plant diseases, i.e., i) a long lifespan and the ability to survive in the soil in both an inactive and an active state; ii) host specificity; iii) ease of laboratory multiplication; and iv) economical and ecologically friendly. *Trichoderma* uses a range of mechanisms to manage the phenomenon of bio-control. These mechanisms include its direct presence at the infection site and its ability to passively activate and trigger different biochemical pathways within the plant system. Therefore, a great deal of research has gone into identifying the specific mechanisms that a given BCA uses to function in various experimental conditions [2]. An extensive study of the functions of *Trichoderma* species as biocontrol agents was presented by [3], emphasizing the latter's capacity to improve nutrient intake and create systemic resistance in plants.

Trichoderma, a genus of filamentous fungi, has gained significant attention in the field of agriculture because of its remarkable ability as a biocontrol agent and plant growth stimulator. These fungi are ubiquitous in the soil and rhizosphere, where they thrive and establish multitrophic interactions with various organisms, including plants and arthropods. The biocontrol potential of *Trichoderma* is well-documented, as it is effective against a wide range of soil-borne and foliar plant pathogens. The versatility of *Trichoderma* in occupying diverse ecological niches can be attributed to its nutritional adaptability and ability to produce a variety of secondary metabolites, enzymes, and other compounds that inhibit the growth of harmful microorganisms [4, 5]. One of the key mechanisms by which *Trichoderma* exerts its biocontrol activity is through the production of potent inhibitory molecules, such as gliovirin and siderophore. These compounds can directly suppress the growth and development of phytopathogenic microorganisms, thus protecting plants from disease. In addition to its biocontrol activities, *Trichoderma* also plays a crucial role in stimulating plant growth and development. Endophytic associations between *Trichoderma* and the seeds and roots of host plants can result in enhanced plant growth, improved crop productivity, and alleviation of abiotic stress. Such beneficial effects are mediated through the activation of endogenous mechanisms controlled by phytohormones, such as auxins and abscisic acid, as well as by alterations in host plant metabolism [6]. Known for their widespread occurrence in soil and root ecosystems, *Trichoderma* spp. are celebrated for their capabilities in biological control of plant diseases and as biostimulators of plant growth.

Recent research highlights the efficacy of *Trichoderma* species in managing a variety of plant pathogens through

mechanisms such as mycoparasitic, competition for nutrients and space, and the production of antimicrobial compounds [7]. *Trichoderma* has been found to enhance plant growth by improving nutrient uptake, promoting root development, and inducing systemic resistance against plant pathogens [8]. These properties make *Trichoderma* a valuable tool in sustainable agriculture, providing an eco-friendly alternative to chemical pesticides and fertilizers. This review discusses recent research that underscores these dual roles, highlighting the mechanisms through which *Trichoderma* species contribute to sustainable agriculture.

2. Environmental Performance of *Trichoderma*

Many important biological control strategies that *Trichoderma* spp. Used to inhibit fungal infections has been highlighted in recent study. *Trichoderma* species employ various tactics, including mycoparasitism, antibiosis, gliotoxin, competition, and environmental condition modification. They also produce secondary metabolites, such as peptaibols, gliotoxin, and *Trichoderma*.

2.1. Biocontrol Potential of *Trichoderma*

Biocontrol agents are preferred over chemical pesticides with no harm to the environment and target specific. Live organisms such as parasites, predators, and pathogenic bacteria, viruses, and fungi are examples of biological control agents. The many physicochemical factors to which they are exposed primarily influenced these functions. Therefore, biocontrol exerted by *Trichoderma* strains is sometimes unpredictable. The genetic diversity of strains within *Trichoderma* species and their mechanisms of biocontrol will lead to improved application of the different strains as BCAs [9]. emphasized the efficiency of different microbial strains, including *Trichoderma*, in controlling *Fusarium* wilt caused by *Fusarium oxysporum* strains in cucumber, banana, and tomato. *Trichoderma* generates chitinases and β -1, 3-glucanases, which break down fungal cell walls, and elicit such chitin oligosaccharides and β -glucan that cause systemic or localized resistance in plants [10]. *Trichoderma* is a powerful biocontrol agent that has advantages over traditional pesticide-based crop protection techniques because of these complex mechanisms.

Trichoderma is a genus of fungi that can combat relationships with plants through several mechanisms, such as (1) Competing for resources; (2) producing antifungal metabolites; (3) Stimulating plant defense mechanisms; (4) Engaging in mycoparasitism, where it directly attacks and degrades pathogenic fungi [11]. *Trichoderma* provides a more environmentally friendly and long-lasting disease treatment option. They support a balanced ecology by assisting in lowering dependency on chemical treatments. *Trichoderma* employs a variety of strategies, including competition, antibiosis, my-

coparasitism, and inducing plant defense responses, to function as a powerful biocontrol agent against plant infections.

2.2. Plant-Defense Mechanisms

Trichoderma species produce secondary metabolites like peptaibols, gliotoxin, and chitinases that inhibit fungal growth by degrading the cell walls of pathogens. Additionally, Trichoderma can induce systemic or localized resistance in plants by producing elicitors that activate plant defense mechanisms, promoting plant growth and nutrient uptake. Potential for these communities to enhance plant health and disease management strategies [12]. According to studies, Trichoderma isolates like *T. Chinese* and *T. citrinoviride* are potential substitutes for synthetic chemical fungicides in agriculture because they efficiently suppress soil-borne pathogens like *Pythium aphanidermatum*, lowering disease incidence and promoting plant growth. The efficacies of *Trichoderma ghanese* and *Trichoderma citrinoviride* against *Pythium aphanidermatum*, the pathogen that causes cucumber damping-off disease, were studied. Trichoderma's antifungal properties are because of its production of metabolites that cause morphological changes in the pathogen's mycelium, leading to significant malformations in *P. aphanidermatum* mycelia [13]. In plant tissues, Trichoderma promotes the deposition of structural polymers like glycoproteins and lignins. These substances fortify the plant's physical defenses against pathogens, increasing its resistance to invasions [14]. Subsequent generations may inherit the favorable effects of Trichoderma on plant health, suggesting a long-term influence on plant development and resilience. Highlighting the potential of Trichoderma that leads to a solution for sustainable disease management in agriculture.

2.3. Mycoparasitism and Antibiosis

Trichoderma-mediated plant pathogen biocontrol relies heavily on mycoparasitic and competition. Differentially expressed genes (DEGs) are regulated by Trichoderma species, including *Trichoderma virens* and *Trichoderma harzianum*, which display mycoparasitic behavior by identifying and penetrating host cells and efficiently eliminating plant diseases like *Rhizoctonia solani*.

This study analyzes the genome and transcriptome of *T. harzianum* T4 access gene expression during contact with *Rhizoctonia solani* and examined the molecular mechanisms influencing *T. Hrozy*'s infiltration. [15]. Trichoderma is effective against a wide range of phytopathogens. Recent studies have investigated the antagonistic effects of Trichoderma, a species (*T. harzianum*, *T. koningiopsis*, *T. asperellum*, *T. tomentosum*, and *T. virens*) on *Colletotrichum*, the pathogen that causes anthracnose in pecans, in vitro. Techniques are crucial for assessing antagonistic activity using inhibition tests and dual culture assays. Significantly, the ability to produce volatile metabolites and the degree of antagonism

exhibited by *Trichoderma virens* and *T. tomentosum* are key factors influencing their biocontrol potential [16]. This mechanism is crucial in controlling soil-borne diseases in crops and developing Trichoderma as an effective biocontrol agent.

2.4. Antimicrobial Compound Production

Trichoderma species are known for their production of antimicrobial compounds, making them valuable biocontrol agents against plant pathogens. This genus of species and many more compounds are being identified daily because of advancements in technology. Production of Secondary Metabolites (SM) is the primary focus of research on Trichoderma. Trichoderma species are helpful in their ability to regulate biological processes and potentially produce bioactive compounds with antibacterial properties, making them essential for the production of natural fungicides. Recent research on Trichoderma strains of *Trichoderma asperellum* and *Trichoderma atroviride* exhibit significant antifungal activity against a range of pathogenic fungi and oomycetes with Minimum fungicidal concentration (MFC) values ranging from 0.19 to 6.25 mg/mL, showing their potential as effective biocontrol agents. The direct contact method resulted in the highest percentage of radial growth inhibition (76% for *T. asperellum* and 81% for *T. Atroviride*). A total of seven classes of volatile organic compounds (VOCs) and twelve nonvolatile organic compounds (VOCs) molecules were identified through GC-MS and HPLC-Q-TOF-MS analyses, which may contribute to their antifungal properties. It could be developed into an environmentally friendly alternative to synthetic fungicides [17]. Trichoderma fungus, found in plant roots, enhances nutrient intake and disease resistance by producing secondary metabolites that activate defense mechanisms and inhibit pathogen growth. Trichoderma-derived metabolites could be a sustainable alternative to chemical fungicides, aiding in disease management and promoting environmental sustainability by reducing agricultural chemical inputs [18]. One of the significant research for the design of new antimicrobial agents and cytotoxic drugs for cancer treatment from the derivatives of trichodermin, particularly those with a short chain at the C-4 position, exhibited selective antimicrobial activity against *Candida albicans*. Cytotoxic selectivity of certain derivatives against the MCF-7 breast carcinoma cell line but not against the non-tumoral Fa2N4 human hepatocytes, suggesting a targeted approach in cancer treatment. The significance of trichodermin derivatives could lead to the development of more effective therapeutic agents and enhance the knowledge of their biological activities [19].

3. Plant Growth Promotion

Microorganisms such as algae, actinomycetes, bacteria, fungi, and protozoa are abundant in soil. The diverse collection of nonpathogenic fungi known as plant

growth-promoting fungi (PGPFs) can be found in the rhizosphere, on the surfaces of plant roots, or inside plant roots. Plant growth-promoting microbes (PGPMs) in soils comprise both fungi (PGPF) and rhizobacteria PGPR [20]. Recent developments in our knowledge of the interactions between plants and PGPMs have given us profound insights into the precise molecular mechanisms behind these beneficial interactions in adverse environmental settings. Trending research explores the potential of beneficial microorganisms as sustainable alternatives to environmental stressors in crop protection.

3.1. Nutrient Solubilization

The free-living fungi known as *Trichoderma* spp., are found in almost all terrestrial habitats. These soil fungi can promote plant development, improve macro- and micronutrient intake, and enhance plant water uptake. The importance of particular fungi's capacity to solubilize insoluble phosphates for plants to acquire phosphorus. Because of their proven effectiveness in this process, fungi such as *Aspergillus*, *Penicillium*, and *Trichoderma* are crucial parts of commercial microbial products meant to increase soil fertility. This implies that employing the utilization of these microbes can help promote more environmentally friendly farming methods by lowering the need for chemical fertilizers. This study examines previous research and conclusions regarding mycorrhizal fungi, as well as how effective they are at acquiring nutrients. [21]. Several important fungi are identified, including *Trichoderma* species, which are associated with plant roots and function as biological control agents against plant diseases. They should be studied to improve plant health and nutrient uptake because of their dual roles. In a recent study, researchers evaluated the in vitro potential of various *Trichoderma* spp. isolates to solubilize calcium phosphate in a specific culture medium (PVK) and investigate the ability to acidify the medium and produce phosphatase enzymes, which are critical for phosphate solubilization. The researchers used a specific culture medium known as PVK (Pikovskaya's medium), which is designed to promote the solubilisation of calcium phosphate. During the examined time intervals, ICB08 (*T. asperellum*) solubilized higher amounts of phosphate than the other isolates. This shows that it can be a very strong phosphate solubilisation agent [22]. The effective Phosphate -solubilization process of *Trichoderma* aids plant nourishment. A recent study, which also emphasizes its role in nutrient solubilization, highlights the potential of this approach in sustainable agriculture methods.

3.2. Projection of Growth-Promoting Hormones

Plant growth hormones are signaling molecules produced within plants that control all aspects of plant growth. Plant hormones are not nutrients but chemical substances that, in small amounts, impact and stimulate the growth, development,

and differentiation of cells and tissues. It's also known as "phytohormones". Generally, plant growth promotion by *Trichoderma* is a consequence of the activity of potent fungal signaling metabolites diffused in soil with hormone-like activity. Key compounds include indolic compounds like indole-3-acetic acid (IAA), which are produced in varying concentrations, and volatile organic compounds such as sesquiterpene isoprenoids and 6-pentyl-2H-pyran-2-one (6-PP) and it can lead to significant biochemical changes in plants, affecting their content of carbohydrates, amino acids, organic acids, and lipids. It has been observed in various plant species, including *Arabidopsis thaliana*, maize, tomato, and barley. The importance of *Trichoderma* spp. In promoting plant growth, enhancing nutrient acquisition, and providing resilience against environmental stresses has been studied [23]. *Trichoderma* species are effective bio-fertilizers, and their ability to produce phytohormones to enhance plant growth.

According to recent findings, *Trichoderma* isolates from the olive ecosystem have a significant potential to generate biomolecules known to promote plant growth. (PGP). *Trichoderma harzianum* T11 (OL587563) was the most promising strain among the isolates that were evaluated. Through in vitro screening, the ability of the isolated strains were produce plant growth metabolites, phytohormone quantification, phosphatase solubilization, and HPLC precise method to measure the concentration of phytohormone (IAA- Indole 3-acetic acid) to be tested. The capacity to generate substantial quantities of advantageous biomolecules makes it a competitive substitute for the growth of olive crops. They emphasize the importance of conducting field studies to evaluate the efficiency of the T11 strain in real soil-plant systems and the use of *Trichoderma harzianum* T11 as a bio-fertilizer, which could contribute to sustainable agricultural practices, particularly in olive farming [24].

3.3. Root Colonization Mechanisms

A mycorrhizal association occurs when a fungus invades the root tissues of the host plant, either extracellularly with ectomycorrhizal fungi or intracellularly in arbuscular mycorrhizal fungi. From the symbiotic association between plants and fungi, fungi help nutrient uptake to the plant through association. *Trichoderma* species have a well-established history of stimulating aboveground biomass growth and generating phytohormones that boost root development. According to comparative genomics research, the lifestyle of *Trichoderma* underwent a transition in a later evolutionary event that resulted in root colonization, endophytism, and the development of stable and advantageous partnerships with plants. Provided a wealth of information that enabled a deeper understanding of this important fungal genus. *Trichoderma* is a beneficial fungus found in soil and root ecosystems worldwide. *Trichoderma atroviride*, *Serenipita indica*, and *S. vermifera* promote plant growth when

they colonize the roots of host plants. Particularly in the field of Trichoderma research, the relationship between plant roots and Trichoderma species is beneficial, leading to an improvement in the plant's immune responses referred to known as “Priming of Defences”. They identified various genes and proteins that are regulated differently in various tissues of maize after inoculation with *Trichoderma atroviride* and conducted a time-course expression experiment to monitor changes from the initial interaction with *T. atroviride*, through the plant's growth, and during an infection by *Colletotrichum graminicola*, a pathogen that affects maize. To examine the function of epigenetic modifications as well, which are modifications to gene expression without changing the underlying DNA sequence, these epigenetic markers contribute to the prolonged activation of the primed state in maize plants, we devised assays to evaluate chromatin structure and changes [25]. However, [26, 27] noted that while Trichoderma shows promise, the variability in colonization success across different plant species suggests that further research is needed to optimize its application in diverse agricultural settings [28–30]. From the Overall findings, Trichoderma's role in root colonization presents a valuable avenue for enhancing plant health and productivity.

4. Conclusion

Trichoderma is a highly versatile and beneficial fungus that plays a crucial role in modern agriculture and environmental sustainability it is a vital component of sustainable agricultural operations because of its capacity to function as a natural biocontrol agent, encourage plant development, improve soil health, and increase plant resilience to diseases. With applications ranging from agriculture and horticulture to bioremediation and aquaculture, Trichoderma offers eco-friendly solutions that reduce the reliance on chemical inputs, promote healthier crops, and contribute to the overall health of ecosystems. The significance of Trichoderma in influencing the direction of agriculture is increasing as the demand for organic and sustainable farming grows.

Abbreviations

BCA	Biological Control Agent
DEG	Differently Expressed Genes
SM	Secondary Metabolites
MFC	Minimum Fungicidal Concentration
VOC	Volatile Organic Compounds
PGPF	Plant Growth-promoting Fungi
PGPM	Plant Growth-promoting Microbes
PVK	Pikovskaya's Medium
IAA	Indole-3-Acetic Acid
HPLC	High- Performance Liquid Chromatography
DNA	Deoxy-Ribo Nucleic Acid

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Author Contributions

Yogasankari Raju: Conceptualization, Data curation, Formal Analysis, Methodology, Resources, Software, Writing – original draft, Writing – review & editing

Ganesh Punamalai: Conceptualization, Investigation, Supervision, Validation

Conflicts of Interest

The authors declare no conflicts of interest.

References

- [1] Tyśkiewicz, R., Nowak, A., Ozimek, E., & Jaroszuk-Ścisiel, J. (2022). Trichoderma: the current status of its application in agriculture for the biocontrol of fungal phytopathogens and stimulation of plant growth. *International Journal of Molecular Sciences*, 23(4), 2329. <https://doi.org/10.3390/ijms23042329>
- [2] Sharma K. (2018b). Trichoderma in Agriculture: An Overview of the Global Scenario of Research and its Application. *International Journal of Current Microbiology and Applied Sciences*, 7(08), 1922–1933. <https://doi.org/10.20546/ijcmas.2018.708.221>
- [3] Harman, G. E. (2006). Overview of Mechanisms and Uses of Trichoderma spp. *Phytopathology*, 96(2), 190–194. <https://doi.org/10.1094/phyto-96-0190>
- [4] Mukhopadhyay, R., & Kumar, D. (2020). Trichoderma: a beneficial antifungal agent and insights into its mechanism of biocontrol potential. *Egyptian Journal of Biological Pest Control*, 30(1). <https://doi.org/10.1186/s41938-020-00333-x>
- [5] Alfiky, A., & Weisskopf, L. (2021). Deciphering Trichoderma–Plant–Pathogen Interactions to improve the development of biocontrol applications. *Journal of Fungi*, 7(1), 61. <https://doi.org/10.3390/jof7010061>
- [6] Macías-Rodríguez, L., Contreras-Cornejo, H. A., Adame-Garnica, S. G., Del-Val, E., & Larsen, J. (2020). The interactions of Trichoderma at multiple trophic levels: inter-kingdom communication. *Microbiological Research*, 240, 126552. <https://doi.org/10.1016/j.micres.2020.126552>
- [7] Woo, S. L., Pepe, O., & Lorito, M. (2022). Trichoderma: a multipurpose beneficial Fungus for agriculture. *Plant Pathology Journal*, 38(4), 341–350.

- [8] Mukherjee, P. K., Horwitz, B. A., Herrera-Estrella, A., Schmoll, M., & Kenerley, C. (2021). Trichoderma research in the genome era. *Annual Review of Phytopathology*, 51, 105–129.
- [9] Keswani, C., Mishra, Sandhya. Sarma, B., Singh, S. P., & Singh, and H. Singh (2013). Unravelling the efficient applications of secondary metabolites of various Trichoderma spp. *Applied Microbiology and Biotechnology*, 98, 533–544. <http://doi.org/10.1007/s00253-013-5344-5>
- [10] Oyesola, O. L.; Tonjock, R. K.; Bello, A. O.; Taiwo, O. S.; Obembe, O. O. Trichoderma: A Review of Its Mechanisms of Action in Plant Disease Control. Preprints 2024, 2024051378. <https://doi.org/10.20944/preprints202405.1378.v1>
- [11] Mahapatra, B., Ghosh, D., & Mukhopadhyay, R. (2024). Biocontrol potential of Trichoderma and Pseudomonas: A review. *International Journal of Advanced Biochemistry Research*, 8(4S), 129–132 <https://doi.org/10.33545/26174693.2024.v8.i4sb.933>
- [12] Niu, B., Wang, W., Yuan, Z., Sederoff, R. R., Sederoff, H., Chiang, V. L., & Borriss, R. (2020). Microbial interactions within Multiple-Strain Biological Control Agents impact Soil-Borne plant disease. *Frontiers in Microbiology*, 11. <https://doi.org/10.3389/fmicb.2020.585404>
- [13] Al-Shuaibi, B. K., Kazerooni, E. A., Al-Maqbali, D., Al-Kharousi, M., Al-Yahya'ei, M. N., Hussain, S., Velazhahan, R., & Al-Sadi, A. M. (2024). Biocontrol Potential of Trichoderma Ghanense and Trichoderma Citrinoviride toward Pythium aphanidermatum. *Journal of Fungi*, 10(4), 284–285. <https://doi.org/10.3390/jof10040284>
- [14] Ge, Barowska, E., Pla, Skowska, E., & Moliszewska, E. (2023). The role of Trichoderma fungi in inducing defense mechanisms in plants. In *Elsevier eBooks* (pp. 179–189). <https://doi.org/10.1016/b978-0-323-91734-6.00010-7>
- [15] Wang, Y., Wang, J., Zhu, X., & Wang, W. (2024). Genome and transcriptome sequencing of Trichoderma harzianum T4, an important biocontrol fungus of Rhizoctonia solani, revealed genes related to mycoparasitism. *Canadian Journal of Microbiology*, 70(3), 86–101. <https://doi.org/10.1139/cjm-2023-0148>
- [16] Poletto, T., Fantinel, V. S., Muniz, M. F. B., Quevedo, A. C., Strahl, M. A., Poletto, I., & Stefenon, V. M. (2024). Efficacy of five trichoderma species against anthracnose pathogens in Pecan through mycoparasitic and antibiosis. *Deleted Journal*, 76(3), 673–681. <https://doi.org/10.1007/s10343-024-00986-w>
- [17] Ruangwong, O., Pornsuriya, C., Pitija, K., Sunpapao, A. (2021). Biocontrol Mechanisms of Trichoderma koningiopsis PSU3-2 against Postharvest Anthracnose of Chili Pepper. *Journal of Fungi*, 7(4), 276. <https://doi.org/10.3390/jof7040276>
- [18] Stracquadanio, C., Quiles, J. M., Meca, G., & Cacciola, S. O. (2020). Antifungal Activity of Bioactive Metabolites Produced by Trichoderma asperellum and Trichoderma atroviride in Liquid Medium. *Journal of Fungi*, 6(4), 263–264. <https://doi.org/10.3390/jof6040263>
- [19] Barúa, J. E., De La Cruz, M., De Pedro, N., Cautain, B., Hermosa, R., Cardoza, R. E., Gutiérrez, S., Monte, E., Vicente, F., & Colladlo, I. G. (2019). Synthesis of trichodermin derivatives and their antimicrobial and cytotoxic activities. *Molecules*, 24(20), 3811. <https://doi.org/10.3390/molecules24203811>
- [20] Gopalan, N. R., Nikhil, P., Sharma, R., & Mohapatra, S. (2023). Use of microbes as a combative strategy for alleviation of abiotic and biotic stresses. In *Elsevier eBooks* (pp. 175–193). <https://doi.org/10.1016/b978-0-323-99896-3.00010-2>
- [21] Silva, P. V., Pereira, L. M., De Souza Marques Mundim, G., Maciel, G. M., De Araújo Gallis, R. B., & De Oliveira Mendes, G. (2022). Field evaluation of the effect of Aspergillus niger on lettuce growth using conventional measurements and a high-throughput phenotyping method based on aerial images. *PLoS ONE*, 17(9), e0274731. <https://doi.org/10.1371/journal.pone.0274731>
- [22] Ribas, P. P., Rech, R., Matsumura, A. T. S., and Van Der Sand, S. T. (2016). Potencial in vitro para solubilização de fosfato por Trichoderma spp. *SciSpace-Paper*. <https://typeset.io/papers/potencial-in-vitro-para-solubilizacao-de-fosfato-por-3xdlzupm3q>
- [23] Contreras-Cornejo, H. A., Schmoll, M., Esquivel-Ayala, B. A., González-Esquivel, C. E., Rocha-Ramírez, V., & Larsen, J. (2024). Mechanisms of plant growth promotion activated by Trichoderma in natural and managed terrestrial ecosystems. *Microbiological Research* 281, 127621. <https://doi.org/10.1016/j.micres.2024.127621>
- [24] Abdenaceur, R., Farida, B., Mourad, D., Rima, H., Zahia, O., & Fatma, S. (2022). Effective biofertilizers, Trichoderma spp. Isolates with enzymatic activity and metabolites enhancing plant growth. *International Microbiology*, 25(4), 817–829. <https://doi.org/10.1007/s10123-022-00263-8>
- [25] Agostini, R. B., Ariel, F., Rius, S. P., Vargas, W. A., & Campos-Bermudez, V. A. (2022). Trichoderma root colonization in maize triggers epigenetic changes in genes related to the jasmonic and salicylic acid pathways, which prime defenses against Colletotrichum graminicola leaf infection. *Journal of Experimental Botany*, 74(6), 2016–2028. <https://doi.org/10.1093/jxb/erac518>
- [26] Morcuende, J., Martín-García, J., Velasco, P., Sánchez-Gómez, T., Santamaría, Ó, Rodríguez, V. M., & Poveda, J. (2024). Effective biological control of chickpea rabies (Ascochyta rabiei) via activation of systemic phytochemical defenses via Trichoderma root colonization: From strain characterization to seed coating. *Biological Control* 193, 105530. <https://doi.org/10.1016/j.biocontrol.2024.105530>
- [27] Piegza, M., & Łaba, W. (2024). Optimized biosynthesis of lytic enzymes by special Trichoderma citrinoviride. *Environmental Science and Pollution Research*, 31(51), 60869–60879. <https://doi.org/10.1007/s11356-024-35251-0>
- [28] Viterbo, A., Ramot, O., Chernin, L., & Chet, I. (2002). Significant roles of lytic enzymes from Trichoderma spp. in the biocontrol of fungal plant pathogens. *Antonie Van Leeuwenhoek*, 81(1), 549–556. <https://doi.org/10.1023/a:1020553421740>

- [29] Adnan, M., Islam, W., Shabbir, A., Khan, K. A., Ghramh, H. A., Huang, Z., Chen, H. Y., & Lu, G. (2019). Plant defense against fungal pathogens by antagonistic fungi with *Trichoderma* in focus. *Microbial Pathogenesis*, 129, 7–18. <https://doi.org/10.1016/j.micpath.2019.01.042>
- [30] Martínez, F. D., Santos, M., Carretero, F., & Marín, F. (2015). *Trichoderma saturnisporum*, a new biological control agent. *Journal of the Science of Food and Agriculture*, 96(6), 1934–1944. <https://doi.org/10.1002/jsfa.7301>